Proton Driver Magnet Power Supply System

Cezary Jach

BD/EE Support

April 19, 2000

System Top Level Parameters

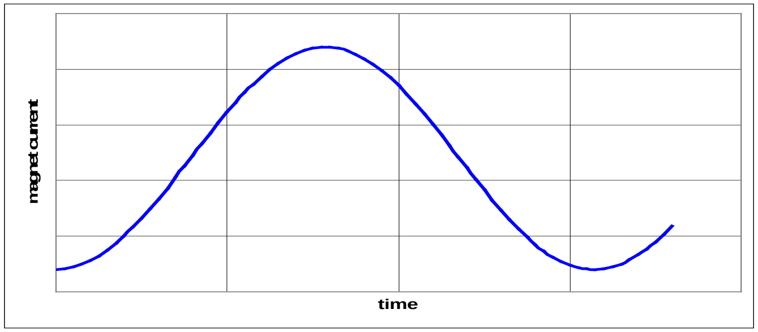
- **Frequency - 15 Hz**
- **Dipole peak stored energy - 9.1 MJ (Main Injector dipole 14.7 MJ @ 120 GeV)**
- **Dipole peak field - 1.52 T**
- **B_{max}/B_{min} = 17.7**
- **Quad. peak stored energy - 2.1 MJ**
- **Quadrupole peak gradient - 8.9 T/m**
- **G_{max}/G_{min} = 17.7**

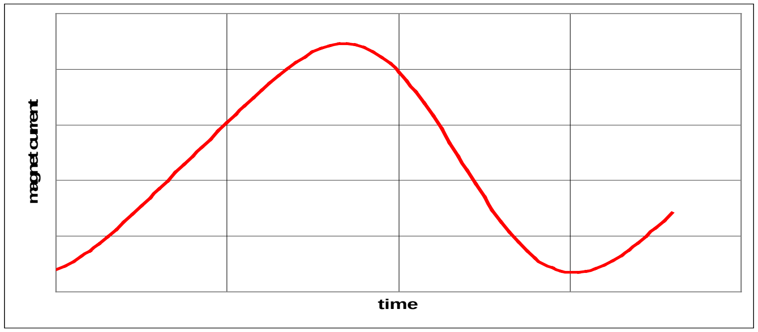
Design Choices

- **SCR power supply system (similar to Main Injector)**
  - **Dipole power supply system S = 550 MVA peak**
  - **Quadrupole power supply system S = 50 MVA peak**
  - **Combined S = 600 MVA peak (Main Ring 300 MVA peak @ 500 GeV), mostly reactive power**
    - **approximately 4 times existing site peak power**
    - **returns reactive power to the grid with 15 Hz frequency**
    - **difficult & costly reactive power compensation**
- **IGBT power supply system (S. Fang)**
- **Resonant power supply system (similar to Booster)**

Resonant Power Supply Systems

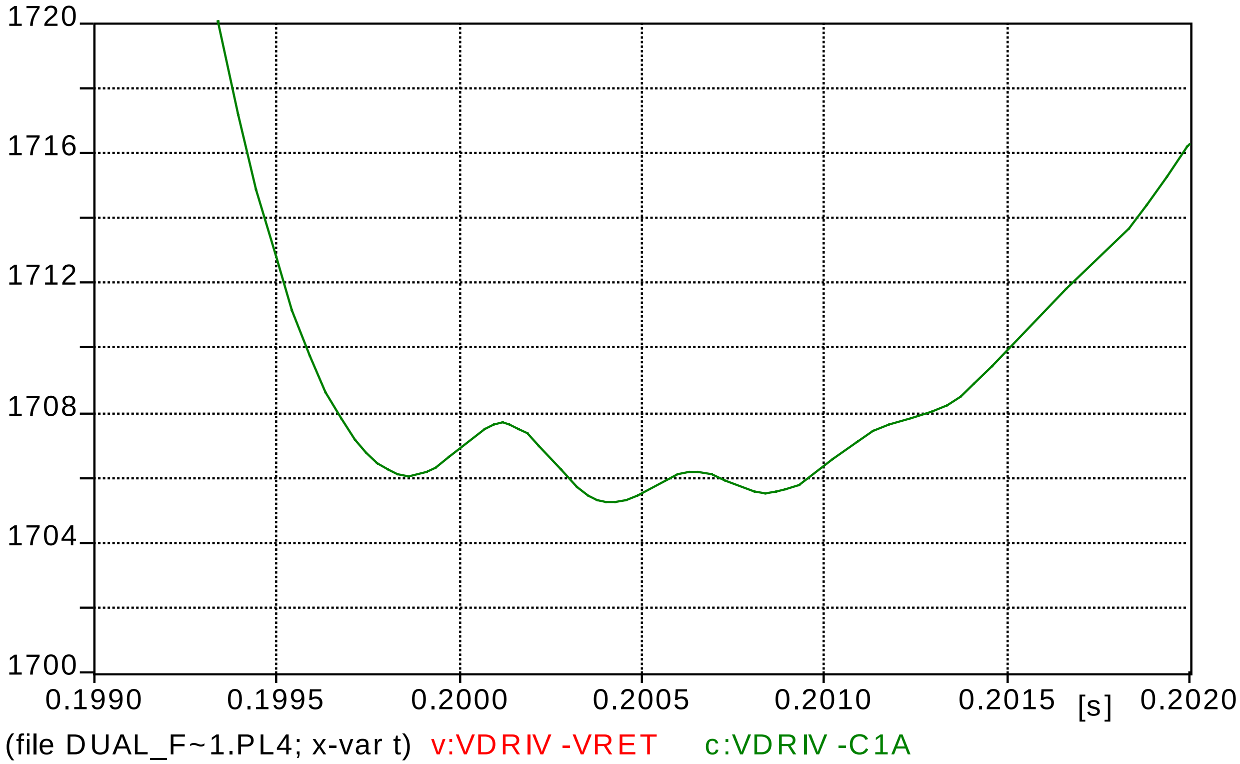
- **Single frequency. Current is in the form of biased sinusoid**
- **Dual frequency. Current is in the form of 15 Hz biased sinusoid with superimposed 30 Hz component- chosen design**
- **Switched. Current is in the form of biased 10 Hz sinusoid when rising, and 30 Hz when falling**





Switched System Magnet Current

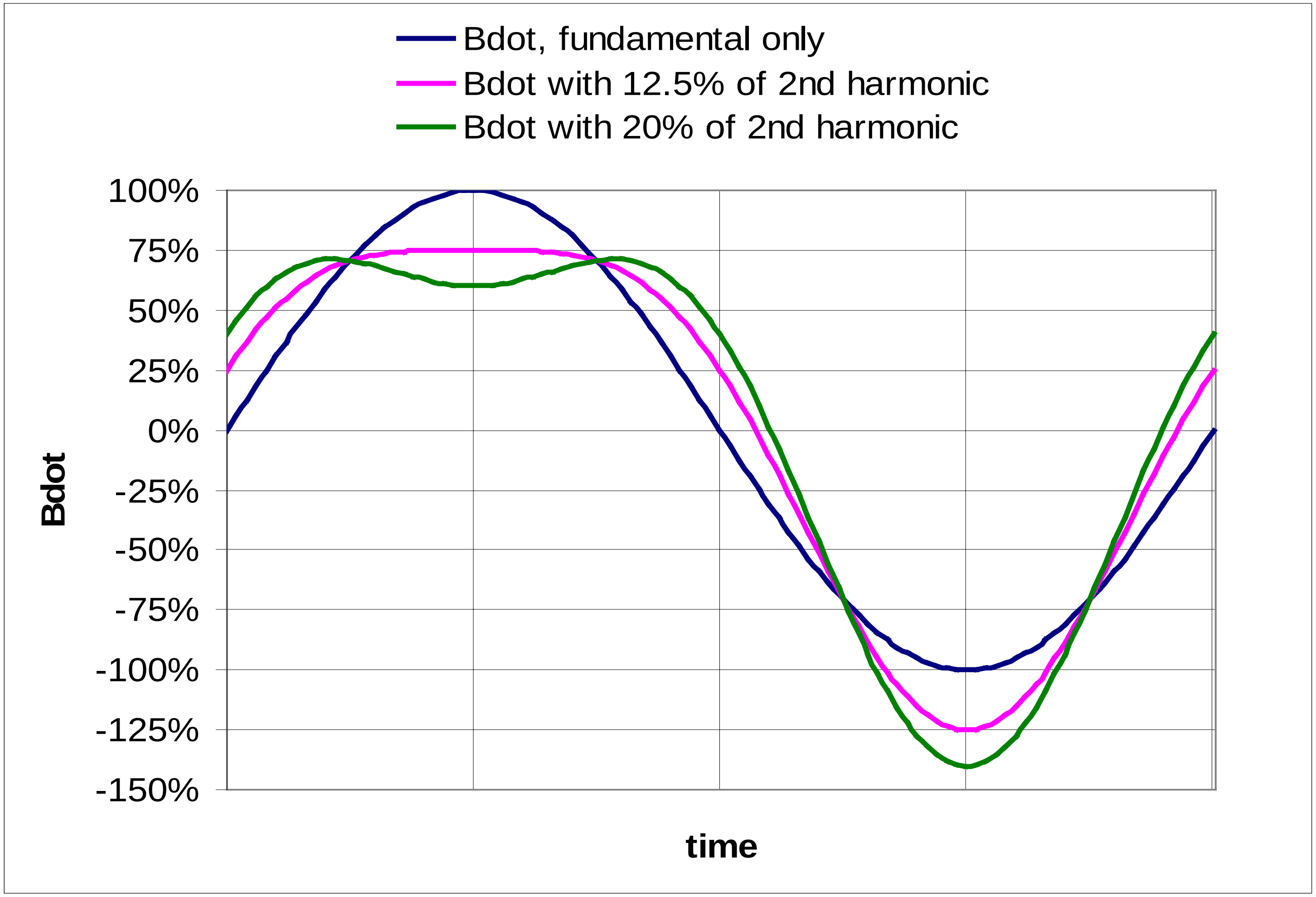
- **Ripple at injection = 270 ppm p-p**



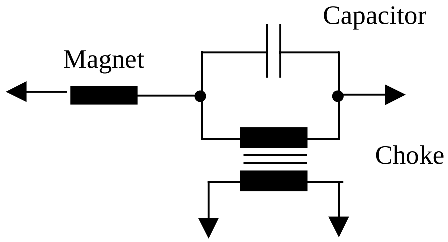
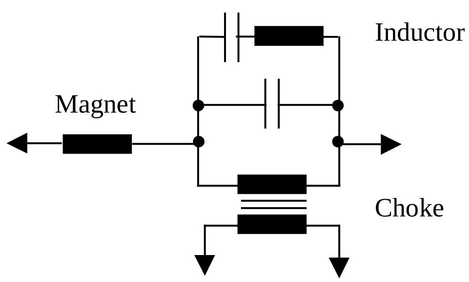
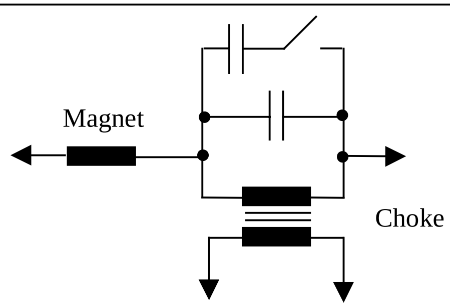
Dual Frequency Resonant Power Supply System

- **LCR network with single resonant frequency at 15 Hz, driven by a source containing 15 Hz and 30 Hz frequencies (30 Hz needs 15 MVA peak)**
- **LCR network with two resonant frequencies at 15 Hz and 30 Hz , driven by a source containing 15 Hz and 30 Hz frequencies - chosen design**

Adding 2nd Harmonic to Magnet Current



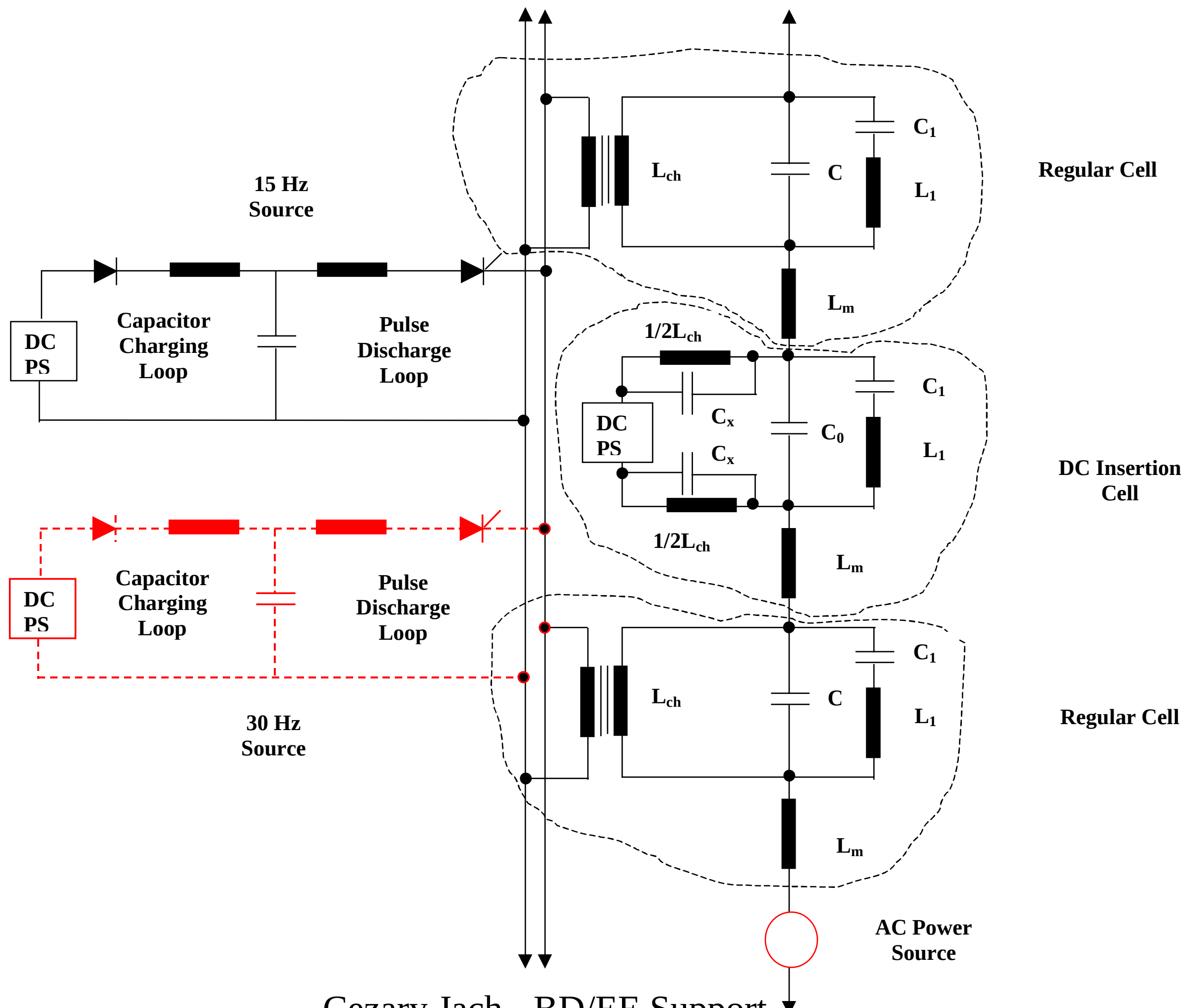
Resonant Power Supply Systems

Single Cell Diagram	System Type	Advantages	Disadvateges
	Single Frequency	• Least complicated • Well understood • Reliable • Many existing systems including Fermi Booster	
	**<u>Dual Frequency</u>** - selected design	• Saves RF power • Reliable • No switching transients	• Higher cost
	Switched	• Saves RF power • Flexibility	• Unknown reliability of switch • Switching transients • Higher cost

Power Supply System Parameters

- **System design based on lattice version 1, dated Jan. 1, 2000**
- **Total induced voltage = 167 kV, number of res. cells = 27**
- **System Voltage**
  - **Voltage across cell, peak = 6,200 V (Booster 940 V)**
  - **Voltage to ground, peak = 3,100 V (Booster 470 V)**
- **Magnet Current**
  - **Peak Current = 7,500 A**
  - **Minimum Current = 420 A**
  - **DC Current = 3,700 A**
  - **AC Current, fundamental, peak = 3,500 A**
  - **AC Current, 2nd harmonic = 440 A**

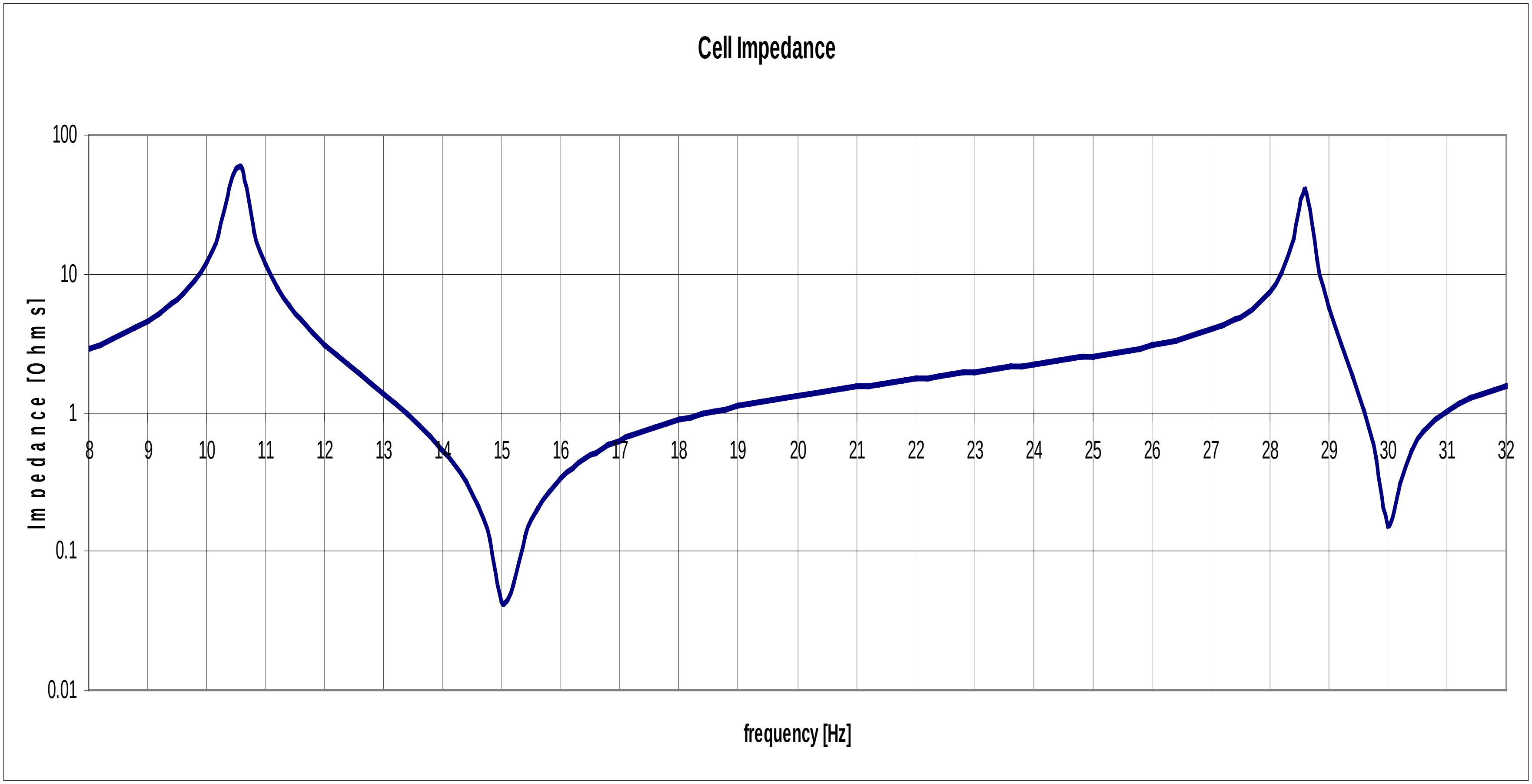
Proton Driver Magnet Power Supply Diagram



Resonant Cell Elements

Resonant Cell Element	Inductance or Capacitance [mH or mF]	DC Resistance [mΩ]	AC Resistance [mΩ]
Equivalent Cell Magnet, L_m	14.7	4.4	12.2
Cell Choke, L_{ch}	18.6	4.5	14.8
Cell Capacitor Bank, C	9.05		1.7
Cell Inductor, L_1	14.8		10.2
Cell Capacitor Bank, C_1	2.88		2.2

Resonant Cell Frequency Response



Power Supply System

- **3.6 MVA of DC power - special cell for DC power supply insertion. Power supply rating - 4.5 MVA**
- **14.5 MVA peak at 15 Hz, either “injected” through secondary windings of dc bypass choke or in series with magnets. Power supply rating - 27.0 MVA**
- **0.8 MVA peak at 30 Hz, either “injected” or in series with magnets. Power supply rating - 1.5 MVA**
- **27 chokes, 100 t, 425 kJ, 3m x 4m x 4m**

Power Supply System Parameters

Parameter	Booster	Proton Driver
Peak Stored Energy [MJ]	0.5	11.2
AC losses, 15 Hz [MW]	0.5	7.3
AC losses, 30 Hz [MW]		0.4
DC losses [MW]	0.8	3.6
Total losses [MW]	1.3	11.3
Q_{15Hz}	21	32
Power supply rating [MVA]	2.8	33

Quadrupole Tracking Error Tolerance Study

1. What is the requirement?

$$\Delta\nu = \left(\frac{\Delta G}{G} - \frac{\Delta B}{B}\right) \times \xi_{uncorrected} + \left(\frac{\Delta p}{p}\right) \times \xi_{corrected}$$

ISIS experience, $\Delta\nu \approx 0.01$

2. What is the reason?

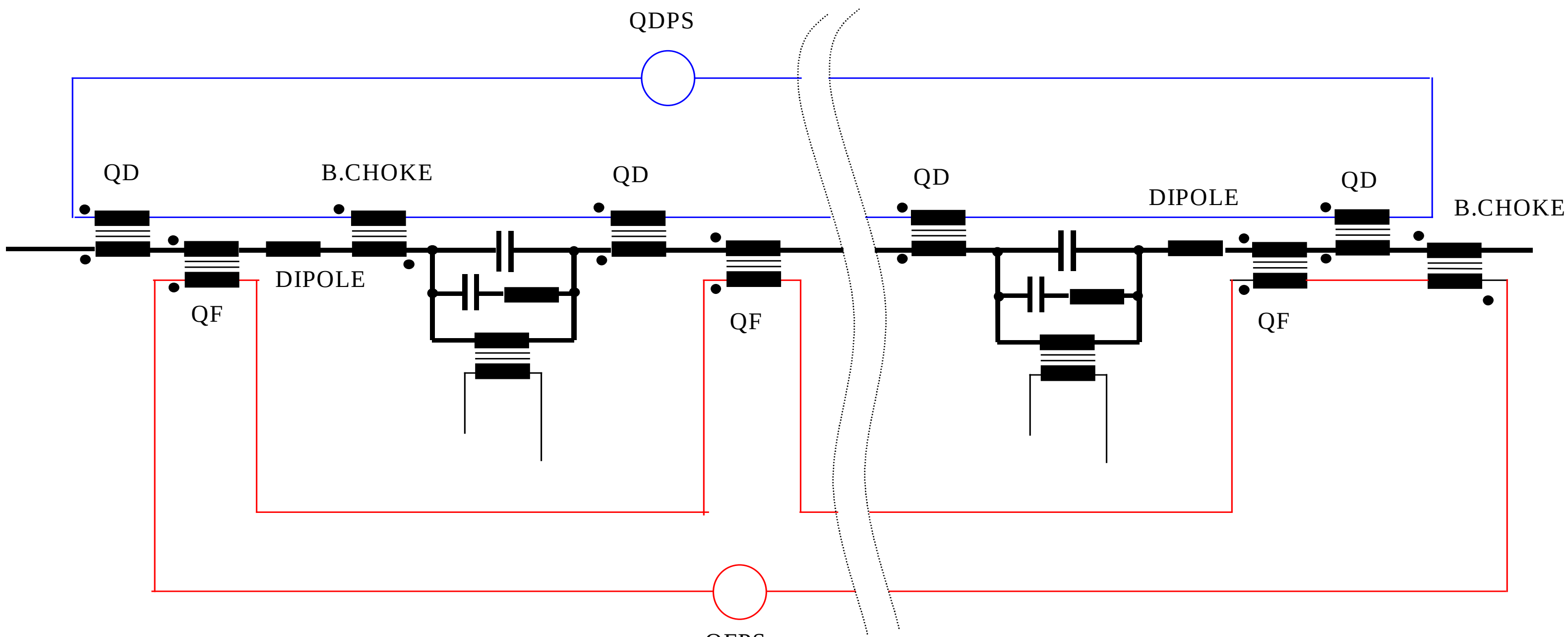
To avoid space charge tune spread edge to touch a 4th order resonant line (space charge = 0.06)

3. Because $\xi_{uncorrected} \approx 10$; $\left(\frac{\Delta G}{G} - \frac{\Delta B}{B}\right) \approx 10^{-3}$

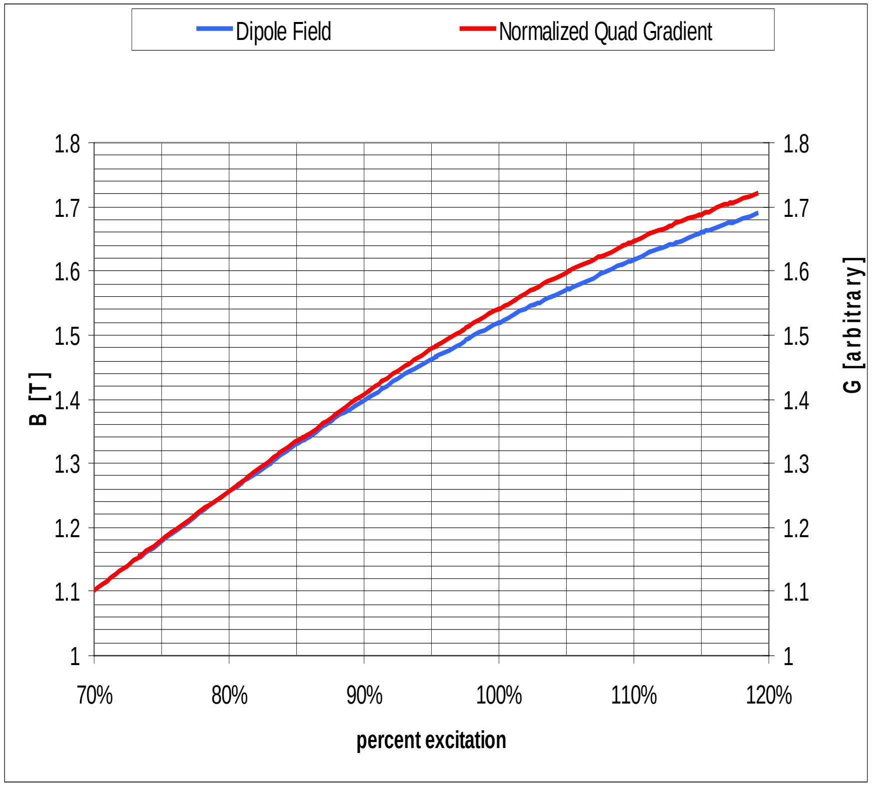
Quadrupole Tracking Power Supply Choices

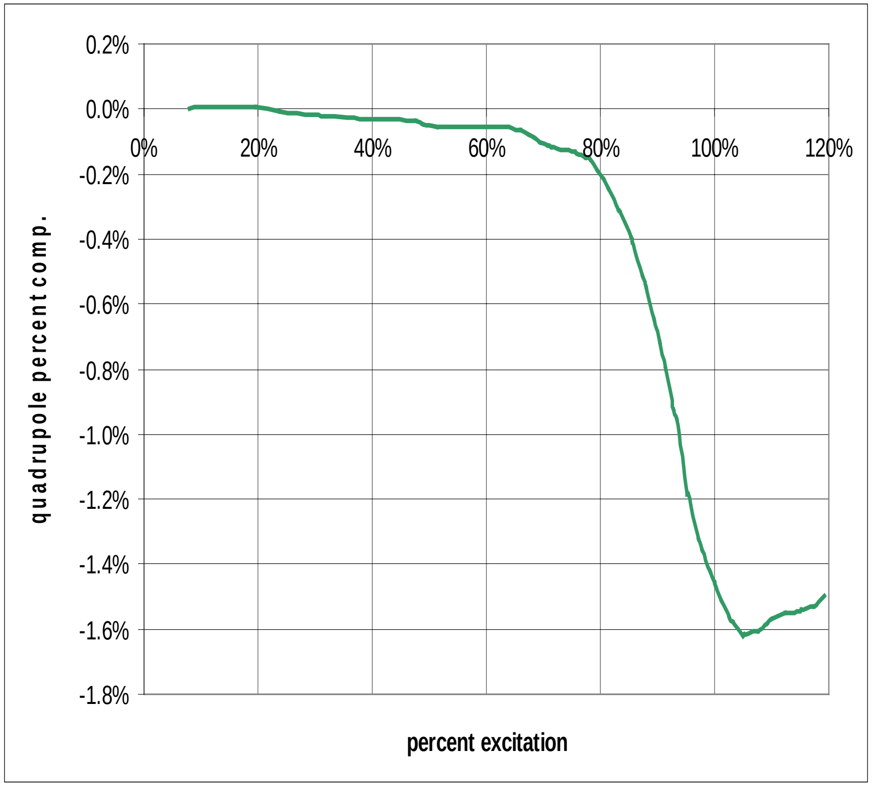
- **Independent power supply circuits**
- **Quadrupole main coils in series with dipoles**
  - **bucking chokes to produce opposing induced voltage**
  - **quadrupole trim coils connected in series with secondary of bucking choke**
  - **IGBT power supplies (Main Injector sextupole power supply style), will meet required current, voltage and bandwidth**

Quadrupole Tracking System Diagram - 1/3 of the Ring

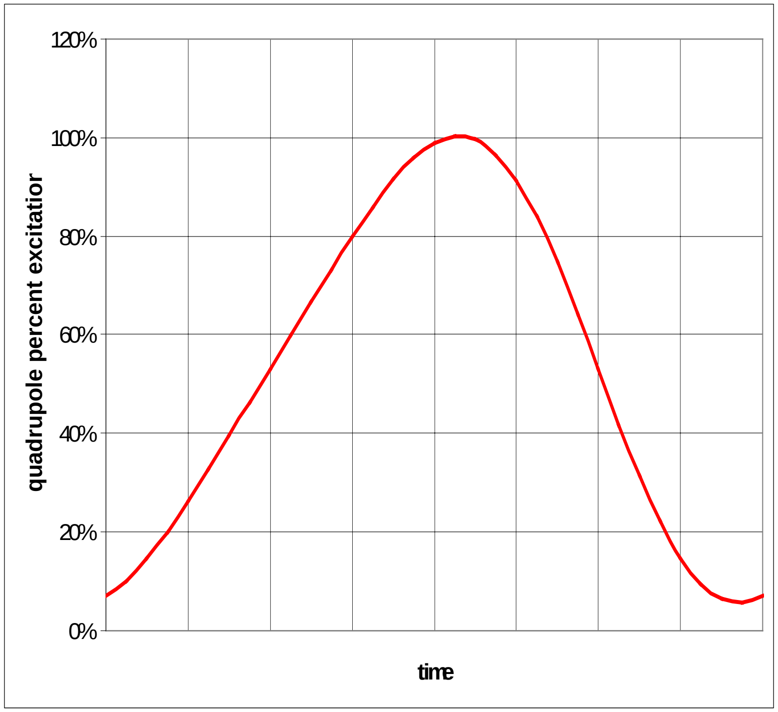


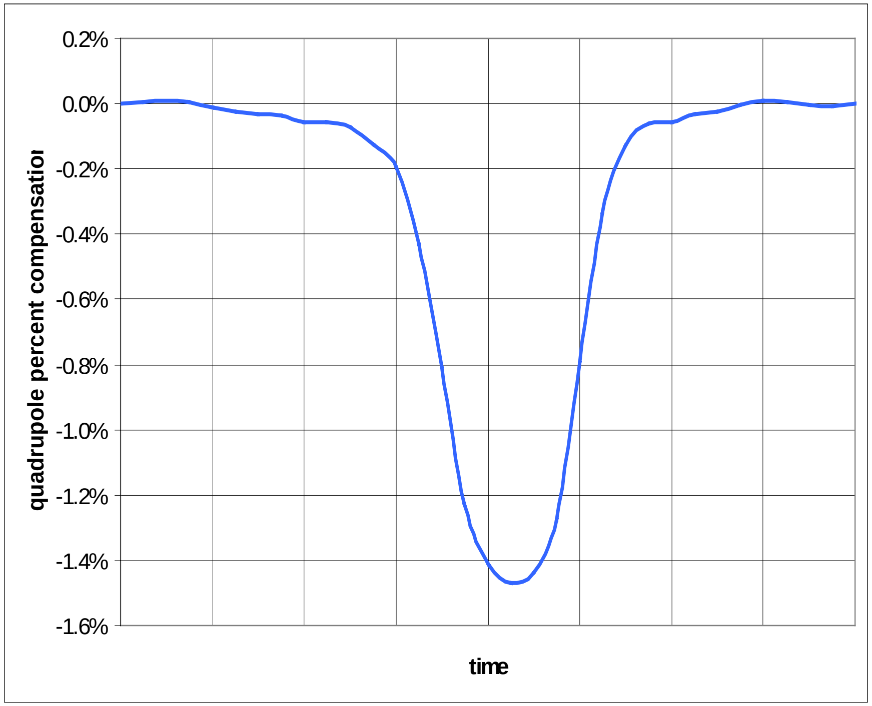
Quadrupole Tracking





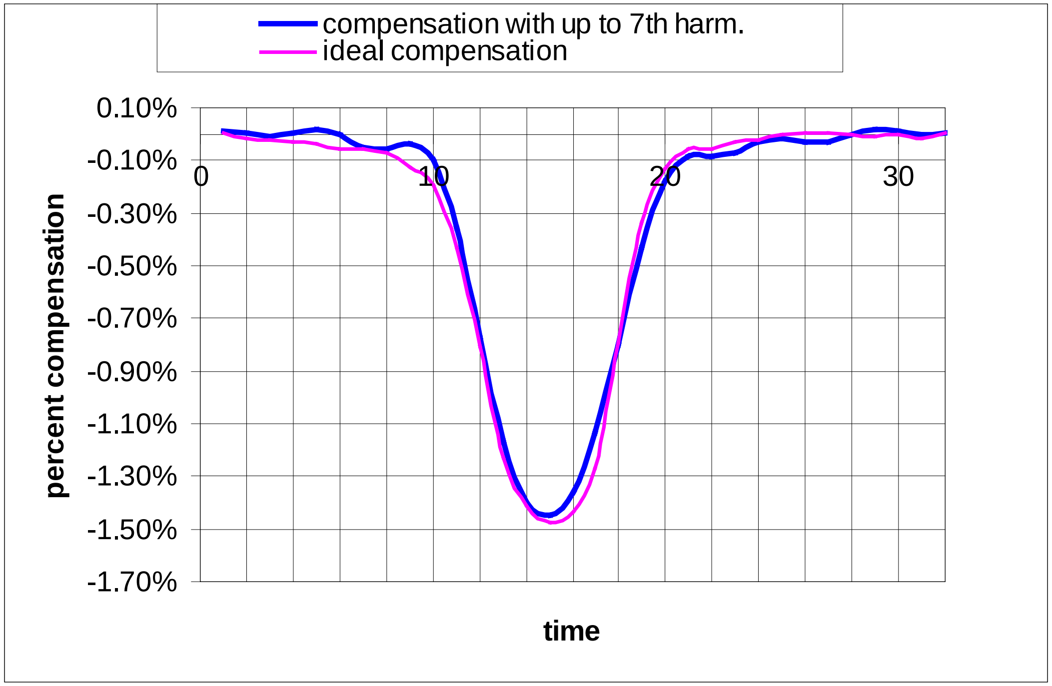
Quadrupole Compensation





Quadrupole Tracking

- **$|\Delta|_{max} \leq$ 0.01% if compensation current includes up to 7th harmonic**



Quadrupole Tracking and Tune Control

- **Power supply peak current rating at given frequency is set by required tune compensation or tracking, whichever is higher**

Frequency [Hz]	Percent Compens. – Tracking [± %]	Percent Compens. – Tune Control [± %]	Power Supply Peak Current Requirement [±%]
15	0.53	2.00	2.00
30	0.36	0.20	0.36
45	0.21	0.10	0.21
60	0.09	0.10	0.10
75	0.02	0.10	0.10
90	0.03	0.10	0.10
105	0.03	0.10	0.10

Quadrupole Tracking Calculations

- **Assume bucking choke's main inductance**
- **Calculate trim circuit input impedance at each frequency**
- **Assume calculated previously required peak currents for each frequency**
- **Calculate required peak voltages for each frequency**
- **Vary quad turns ratio to arrive at reasonable power supply current/voltage ratings**
- **Calculate bucking choke turns ratio**

Quadruple Tracking Circuit Calculation Results

- **Bucking choke requirements:**
  - **L1 = 2 mH, L2 = 4.31 mH, k = 0.98**
  - **N1 = 32, N2 = 47, δ = 0.03%**
  - **74 kJ**
- **Quadrupole turns ratio 4:1**
- **Power supply requirements:**
  - **210 Hz minimum bandwidth**
  - **860 A peak, 608 V peak**
  - **6 power supplies, 608 kVA peak each**
  - **Capable of 4 quadrant operation**

Conclusions

- **Well proven technology**
- **Very large components**
- **More detailed design and complete system simulations will be done after lattice design is stabilized.**
- **Challenges**
  - **3,100 V magnets**
  - **Quadrupole tracking**
  - **Regulation (DC, 15 Hz, 30 Hz)**